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Investigation of islanding operation in a small distribution network with small scale generation unit

Master's thesis in Electric Power Engineering

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Department of Energy and Environment
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Abstract

Since the storm Gudrun in 2005, overhead lines are being replaced by underground cables. However the transition to cables lead to appearance of overvoltages during islanding. In order to analyze the problem, a part of the distribution grid where the problems appeared, is studied.

The study is performed in PSCAD where a simplified model of the grid is built. Simplifications are used for the modelling of the surrounding grid and the customers are represented with lumped constant impedance loads. However, the other components of the system, such as transformers, cables, OHLs and generators are modelled in detail. Different islanding scenarios are simulated based on possible faults in the system. The results are analysed to find what the source of overvoltages and what influence the level of overvoltage.

A loss of connection from the main grid to the local generator causes instabillity and result in over- or undervoltage. A solution is to disconnect all shunt capacitances at the local generation units and install a shunt reactor to compensate for the reactive power generation from the cables. The reactor is only required if the cables reactive power consumption is too high.

Keywords: Islanding, unbalance, local generation, overhead lines, cables, overvoltages, shunt capacitance banks, shunt reactors, reactive power.

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Alfred Andersson, Tom Nilsson

Göteborg, 2014-06-03

List of Abbreviations

Abbreviation	Description	Symbol
AG	Asynchronous Generators	
R	Resistance	$[\Omega]$
OHL	Overhead Line	
SvK	Svenska Kraftnät	
THD	Total Harmonic Distortion	
$XLPE$	Cross-linked polyethylene	
$ACSR$	Aluminium Conductor Steel Reinforced	
GMR	Gemetric Mean Radius	
$L-L$	Line-To-Line Voltage	
SLG	Single Line to Ground	

Contents

Chapter 1

Introduction

Since the beginning of big scale electrical power production the required frequency and voltage are regulated using synchronous generators. It is typically done at large generation power plants, i.e. the hydro power plants in Sweden.

Since the early 1980s most installed generators smaller than 10 MW are asynchronous generators (AG). The drawback with the AG is that it requires reactive power support. For generators connected to medium voltage or low voltage systems the most common solution is to connect a shunt capacitor bank.

The Swedish rural medium voltage network is built with overhead lines (OHL) at a voltage level between 10 kV and 20 kV. Since the storm Gudrun in 2005, the government has set pressure on distribution companies to make the system more weather proof. In practice this means that most of the medium voltage OHL networks in Sweden are or will be replaced by cables, especially in south Sweden. Replacing OHL with cables increases the reactive power production to levels of MVAr in a local medium voltage system.

It is noticed that, especially in medium voltage systems with local AG, high voltages are present during islanding. Typically, when a fault occur on a adjacent line, parts of the distribution network becomes islanded to avoid a propagation of the fault further into the system. It is during islanding the voltage increase. These overvoltages are the reason for damaging electrical devices at costumer homes.

1.1 Background

This thesis is conducted in cooperation with Vattenfall. It is a study of an existing distribution network in Dalsland and the impacts on it during islanding. The focus is on a branch that only is connected at one side and therefore may be islanded. The branch will henceforth be named L1. The branch is today a mix of both OHLs and underground cables. However, Vattenfall is planning to replace all the remaining OHLs with cables over the next few years. The L1 has a local generation unit connected to it and mainly small loads, such as summer houses. Figure 1.1 represent a simple overview of the system.

Since the transition from OHL to cables overvoltages are occurring at the customers in branches with local generation units. Overvoltages on L1 are noticed by Vattenfall during islanding. The tripping of L1 is most often due to a fault on an adjacent line.

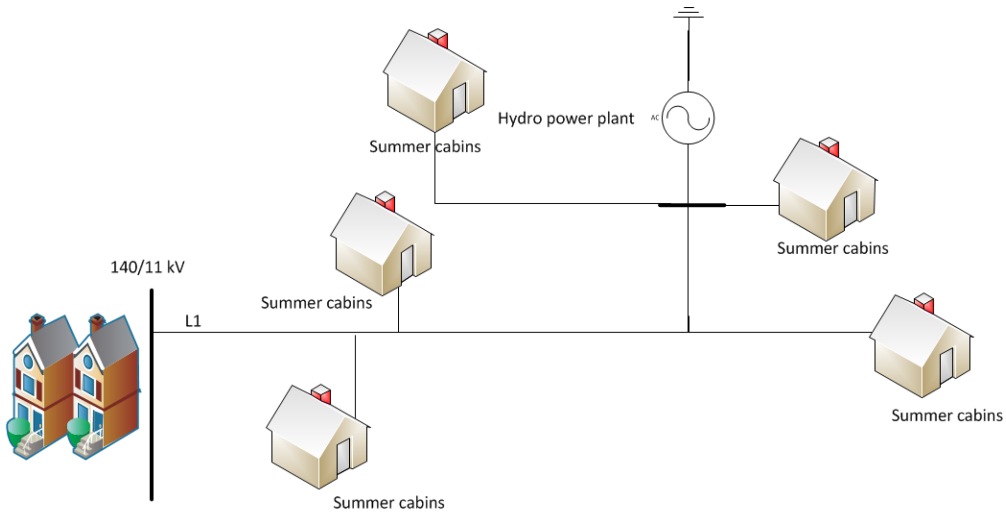


Figure 1.1: Overview of the system.

1.2 Aim

The aim of this thesis is to investigate why L1 is subject to overvoltages during islanding during a SLG fault and find one or more solutions on how to prevent this from occurring in the future.

1.3 Scope

A reduced system is going to be modelled to analyse the system. The goal is to simulate L1, locate the overvoltages and thereafter find and simulate a solution that will lower and possibly eliminate the overvoltages. It is a theoretical study and no measurements or physical experiments are conducted.

The surrounding power system will not be fully modelled due to lack of time and data. Consequently, it will be represented by simplified equivalent loads and generators. Exact voltage amplitudes and exact replicas of the simulation equipment are therefore not crucial.

Voltage rise during islanding of a asynchronous generator it the focus. Although the low voltage may appear as well, it is not of interest since mainly constant load is present.

Over time the loads variates in terms of consumption. This will not be investigated in detail but will discussed during the modeling.

1.4 Method

To simulate a numerous amount of effects in a power system the software PSCAD was used. The focus of the simulations is on high voltages. Other present effects are analysed in a separate section. Only equipment from the standard equipment library in PSCAD is used. The system is too large and detailed to build a complete replica in PSCAD. Therefore, simplifications are made in order to get a manageable model. The purpose of the model is that it is easy to operated and accurate enough to simulate the behaviour of the real system. In order to not compute an excessive amount of simulation scenarios a pre-defined number of model variations are made. At least one of these variation is changed in every new scenario. The scenarios intention is to reveal why the overvoltages occur. A more detailed description of PSCAD, the simplifications and the simulation model is described in a separate chapter.

As an extension to the simulation results an analysis is made. The purpose of the simulations together with the analysis is to highlight and explain the influence from various equipments behaviour. An important part of this is the behaviour of the local generation unit in form of a hydro power plant. There is a lack of complete equipment details for all equipment. The intention of the simulation model is to perform as close to the real system as possible, because of the lack of details it is not to be an exact replica.

From the analysis a discussion and conclusion is made to get a deeper knowledge and understanding in the behaviour of the system. This will help in the future when making decisions in small distribution networks with local generation units.

Additionally, discussions and meetings with experts at Vattenfall are performed to gather knowledge about the system and to ensure that it is behaving accordingly.

Chapter 2

Electric Power Quality

Power quality is a crucial factor of a power system. It is regulated through laws and standards. Power quality includes voltage magnitude and wave shape as well as power availability. To have a good transmission all the way from the power plants in the north to the customers in south is condition for a good voltage level. This chapter introduce the Swedish regulations, standards and laws which are set to reach a desired power quality.

2.1 Swedish power system

The Swedish power grid is divided into three systems; national, regional and local grid. The national level has the highest voltage of 400 kV and is the backbone of the Swedish electrical distribution system. This grid is maintained and run by SvK.

The next voltage level is the regional level at 40 kV or 11 kV. At this voltage level the ownership of the grid is far more open and divided. Overall, the regional grid is owned by 170 companies and the three biggest owners are Vattenfall Electricity Distribution, Fortum Distribution, E.ON Networks Sweden.

The last voltage level in the grid is the local grid at 400 V, this grid is where the customers and most loads are connected [1].

The power quality in Sweden is defined by a number of criterion that describe the characteristics of the voltage. It describes the amplitude, shape and symmetry at connection points. A connection point is where the grid is electrically connected between different grid owners, i.e. between Svenska Kraftnät (SvK) and a regional grid company or between the local grid owner and its end customer. The criterion is used to ensure that bad quality electricity is not transferred between different owners and in the long run correctly delivered to the end customer [2].

2.2 Laws and regulations

The owner of the grid is responsible for the electricity to reach its customers, and that it fullfills the given requirements. The voltage level is specified to stay within a certain limits and it is the grid owners responsibility to meet the requirements. At blackouts and other complications which leads to problems for the customers, the grid owner is responsible to repair the damage and cover the losses for the customer.

In Sweden, the rules for blackouts are regulated by law. The companies has different policies that fullfill this. If a blackout lasts longer than 12 hours, the company owning the grid is required to pay back 12,5 % of the yearly grid cost and if longer than 24 hours 25% [3]. Due to this and other factors, the grid companies concerns about overvoltages and other disturbances are increased. Overvoltages is a source to damages in the system and blackouts. This could result in unwanted economical costs.

2.3 Voltage quality

The voltage quality in the grid is specified as the variation from the ideal voltage that is specified for each voltage level. The required voltage quality in Sweden is determined by Energimarknadsinspektionen together with the laws and directives from the European Union and Elsäkerhetsverket [4]. The requirements stat that the local voltage grid needs to stay within $230 \pm 10\%\ V\ L-G\ RMS$, this is an European standard. It is the criteria for the slow measurement variations that is based on measurements every 10 minutes. At faster measurements the restrictions focus on fast changing voltage levels, the maximum that allowed is 3% [5].

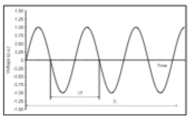
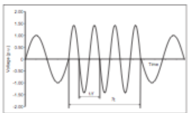
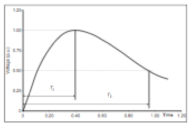
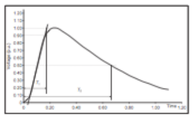
2.4 Overvoltages and transients

The information in this section is based on the IEC 60071 standards on three-phase systems with a nominal voltage > 1 kV. There are six different classifications of voltages and overvoltages, see Table 2.1 [6].

Figure 2.1 illustrates the shapes and parameters for the overvoltages [6].

Table 2.1: Classification of overvoltages.

Type	**Description**
Continuous power frequency voltage	Constant RMS value.
Temporary overvoltage	Present during short-circuits or ground faults. Duration time variates depending on fault. It can be a few second for a short-circuit and up to hours for a ground-fault. The frequency can vary under and above system frequency.
Transient overvoltages	Duration times is a few millisecond, and normally followed by a temporary overvoltage.
Slow-front overvoltage	Often due to switching actions because of short-circuits and ground faults. It is normally unidirectional and a rise time to peak between 20 μs and 5 μs and a tail below 20 ms.
Fast-front overvoltages	Often due to lightning strokes or backward flashover following lightning strokes or a result of switching actions. Mort often unidirectional with a time to peak between 0.1-20 μs and a tail below 300 μs.
Very-fast-front overvoltages	Occurs most often due to disconnecting switches within gas-insulated switchgear. Normally unidirectional with a rise to peak below 0.2 μs and a total duration of max 3 μs. It normally have superimposed oscillations between 30 kHz - 100 MHz [6].

Class	**Low-frequency**		**Transient**	
	Continuous	**Temporary**	**Slow-front**	**Fast-front**
Voltage shape				
Frequency range, time duration	$f = 50\,\text{Hz}$ or $60\,\text{Hz}$ $T_t \geq 3.600\,\text{s}$	$10\,\text{Hz} < f < 500\,\text{Hz}$ $3.600\,\text{s} \geq T_t \geq 30\,\text{ms}$	$20\,\mu\text{s} < T_p \leq 5.000\,\mu\text{s}$ $T_2 \leq 20\,\text{ms}$	$0.1\,\mu\text{s} < T_1 \leq 20\,\mu\text{s}$ $T_2 \leq 300\,\mu\text{s}$
Standardized voltage shape	$f = 50\,\text{Hz}$ or $60\,\text{Hz}$ T_t [a]	$48\,\text{Hz} \leq f \leq 62\,\text{Hz}$ $T_t = 60\,\text{ms}$	$T_p = 250\,\mu\text{s}$ $T_2 = 2500\,\mu\text{s}$	$T_1 = 1.2\,\mu\text{s}$ $T_2 = 50\,\mu\text{s}$
Standardized voltage test procedure	[a]	Short-duration power-frequency test	Switching impulse test	Lightning impulse test

a To be defined by the responsible equipment committees for standardization.
T_p and T_1, time to peak or front time; T_2, time to half-value of tail; T_t, total time duration.

Figure 2.1: Illustrative figure over overvoltages.

Chapter 3

Fault Theory

Faults in a electrical power system can either be symmetrical or unsymmetrical. An unsymmetrical fault is for example a SLG (single line-to-ground), line-to-line or a line-to-line-ground.

3.1 Symmetrical components

It is sufficient in a balanced three-phase system to calculate voltage and current on one phase. This is because the other two phases only are phase shifted from the first. This is only valid for a balanced system. If the system becomes unbalanced this is no longer valid. Then the symmetrical components need to be introduced for simplified analysis [7].

Unbalanced voltages and currents are decomposed into symmetrical components are transformations of the . Three sets of balanced components of the unbalanced voltage and current are made to simplify the calculations.

The symmetrical components of phase currents are written as

$$\begin{vmatrix} I_a \\ I_b \\ I_c \end{vmatrix} = \begin{vmatrix} 1 & 1 & 1 \\ 1 & a^2 & a \\ 1 & a & a^2 \end{vmatrix} = \begin{vmatrix} I_0 \\ I_1 \\ I_2 \end{vmatrix} \tag{3.1}$$

Where I_1 is positive sequence current, I_2 is negative sequence current and I_0 is zero sequence current. $a = -0.5 + j0.866$ and $a^2 = -0.5 - j0.866$.

3.2 SLG fault

Typically 70% of all the faults in a power system is SLG faults [7]. Figure 3.1 represent a SLG fault on phase a in a three phase system.

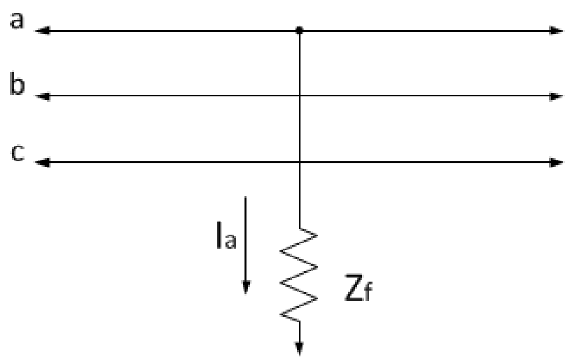


Figure 3.1: Circuit over a SLG fault

Z_f represents the fault impedance to ground. The magnitude of the grounding current depends on the systems grounding in the grid. If there is resistive grounding in the system it will be in series with Z_f. It is assumed that it is a solidly grounded system with zero grounding resistance.

Since phase a has a fault current, phase b and c will be zero. Assuming load current is neglected. This gives a voltage at point a to be $V_a = I_a Z_f$ [7].

The sequent currents will be

$$\begin{vmatrix} I_0 \\ I_1 \\ I_2 \end{vmatrix} = \frac{1}{3} \begin{vmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{vmatrix} \begin{vmatrix} I_a \\ 0 \\ 0 \end{vmatrix} = \frac{1}{3} \begin{vmatrix} I_a \\ I_a \\ I_a \end{vmatrix} \tag{3.2}$$

This gives,

$$I_0 = I_1 = I_2 = \frac{1}{3} I_a \tag{3.3}$$

$$3I_0 Z_f = V_0 + V_1 + V_2 = -I_0 Z_0 + (V_a - I_1 Z_1) - I_2 Z_2 \tag{3.4}$$

The zero sequence current will be

$$I_0 = \frac{V_a}{Z_0 + Z_1 + Z_2 + 3Z_f} \tag{3.5}$$

This gives a fault current of

$$I_a = 3I_0 = \frac{3V_a}{(Z_1 + Z_2 + Z_0) + 3Z_f} \tag{3.6}$$

Implementing a grounding impedance, Z_N, would make it possible to change the fault impedance and affect the current and voltage at the fault.

$$I_a = 3I_0 = \frac{3V_a}{(Z_1 + Z_2 + Z_0) + 3Z_f + 3Z_N} \tag{3.7}$$

3.3 Grounding system

The grounding of a power system have a great impact on the fault voltage and current. Figure 3.2 represents a simple system similar to the investigated system. There are two lines, one where a fault occur and another to represent the rest of the system.

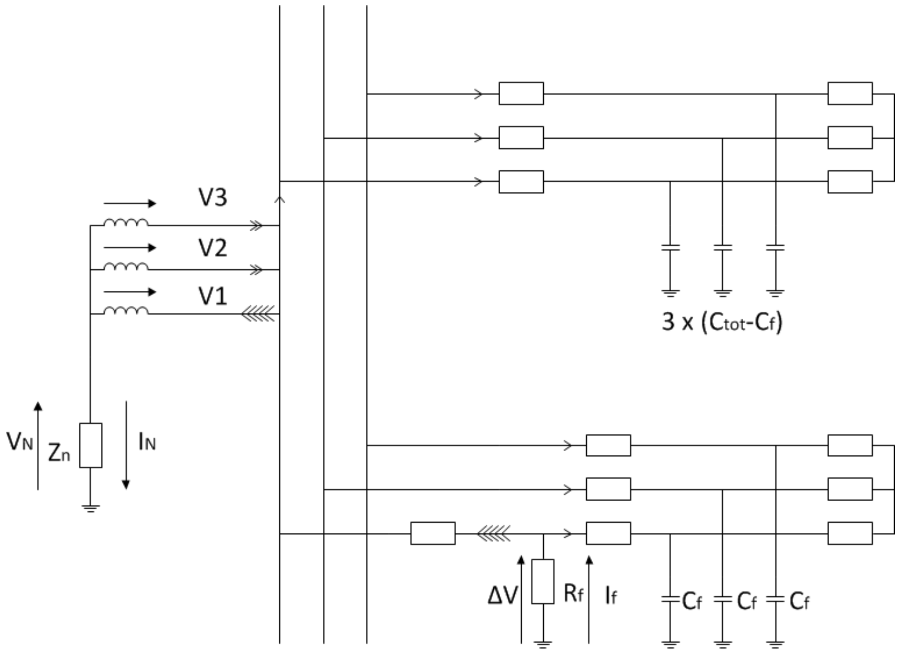


Figure 3.2: Groundning of the investigated system

Z_N represents the grounding impedance in the system, this is where a system grounding protection is installed. R_f represents the fault location and its impedance. On each line there are two impedances. The first represents the line impedance and the second represents a load impedance. The equivalent capacitance-to-ground from the lines are represented by C_f and C_{tot}.

Figure 3.3 represents a residual equivalent circuit of Figure 3.2 which do not refer to load conditions and fault position [8].

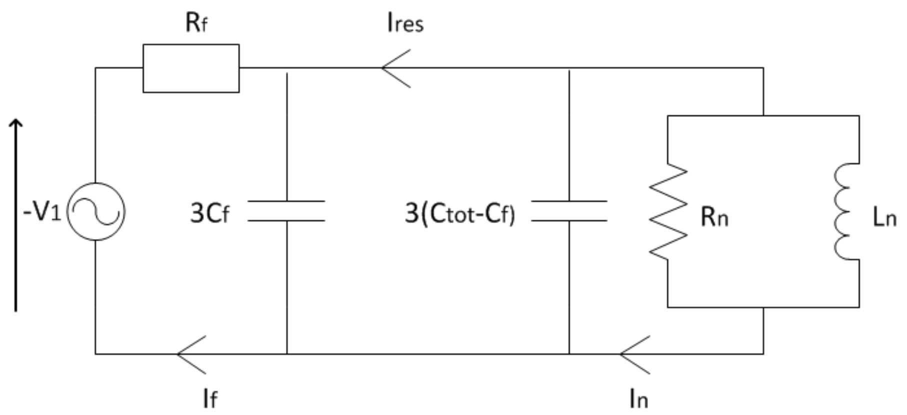


Figure 3.3: Equivalent circuit of the grounding in one phase

If a neutral point protection equipment is installed, i.e. a petersen coil, the cables and system capacitance could be cancelled out by the inductance from the coil, as presented in (3.8). This would leave only the active part of the fault circuit.

$$3C_f + 3C_{tot} = L_N \tag{3.8}$$

Chapter 4

Component Theory

Cables and overhead lines are key components in the investigated system. Therefore, parameters and physical properties of them are thoroughly presented. Additional equipment in the system are not described because standard models are used in the simulations. However, supplementary equipment (i.e. zigzag transformer) and effects (i.e. transformer saturation) are described to get an elementary understanding why it is used in the simulation model.

4.1 Cables and overhead lines

This section presents the basic parameters of cables and OHLs to gain knowledge and understanding in how cables and OHLs affect the system.

The equivalent circuit of OHLs and cables consists of series resistance, series inductance, shunt capacitance and shunt conductance. The resistance depends mainly on the physical composition of the conductor at a specific temperature, length of the line and cross-section of the conductor. The inductance and the capacitance are due to the physical phenomenons of magnetic and electrical fields around the conductor. The shunt conductances represents leakage currents and are often very small. Therefore it is neglected in this thesis [9].

Cables and OHLs are often represented as π-sections with equivalent parameters, see Figure 4.1.

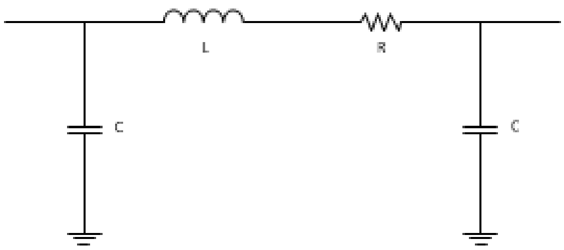


Figure 4.1: Simple π-section of a cable/OHL.

To find the AC resistance of a conductor, the DC resistance is evaluated first. If the DC current through a cylindrical conductor is uniformly distributed along the cross-area, the resistance is calculated by

$$R_{DC} = \frac{\rho l}{A} [\Omega] \tag{4.1}$$

Where ρ is the resistivity, l is the length of the line and A is the cross-section area.

The AC resistance, R_{AC}, is higher than R_{DC} due to the skin effect. Skin effect is when the the frequency forces the current outwards on the edge of the conductor. This makes the effective area of the current smaller and therefore results in a higher resistance. The resistance of a conductor also increases linearly with higher temperature. The AC resistance, R_{AC}, is calculated from the R_{DC} resistance. The constant k is the skin correction factor [9].

$$R_{AC} = R_{DC} * k \tag{4.2}$$

The inductance of a OHL is a lot higher than for a cable. If a conductor is carrying a current it produces a concentric magnetic flux around it. The total magnitude of the magnetic flux depends on the characteristics of the line. To determine the inductance some parameters needs to be calculated. These are field intensity H, density B, and flux linkage λ.

The internal strength of the magnetic field H of a conductor with length l can be calculated by

$$H_x = \frac{I_x}{2\pi x} = \frac{I}{2\pi r^2} x \ [A/m] \tag{4.3}$$

Where x distance from from the center, r is the radius of the conductor and I_x is the current in through the conductor. With this the magnetic flux density B is calculated by

$$B_x = \mu H_x = \frac{\mu_0}{2\pi}(\frac{Ix}{r^2})\ [T] \tag{4.4}$$

where $\mu = \mu_0 = 4\pi * 10^{-7} H/m$ for materials that are non-magnetic. The internal flux linkage λ_{int} is calculated by

$$\lambda_{int} = \frac{\mu_0}{8\pi} I\ [Wb/m] \tag{4.5}$$

The internal inductance due to internal flux linkage is

$$L_{int} = \frac{\lambda_{int}}{I} = \frac{\mu_0}{8\pi} I\ [H/m] \tag{4.6}$$

When evaluating the external inductance, an assumption is made that all the current in the conductor is on the surface. The magnetic field intensity at radius y is

$$H_y = \frac{I}{2\pi y}\ [A/m] \tag{4.7}$$

And the magnetic field density is

$$B_y = \mu H_y = \frac{\mu_0}{2\pi} \frac{I}{y}\ [T] \tag{4.8}$$

The external flux linkage from the conductor to any point D is

$$\lambda_{ext} = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{r}\right)\ [Wb/m] \tag{4.9}$$

The total flux linkage is the summation of internal and external flux linkage. Therefore, the total inductance on the conductor can be calculated.

$$\lambda_{int} + \lambda_{ext} = \frac{\mu_0}{2\pi} I \left(\frac{1}{4} + \ln\left(\frac{D}{r}\right)\right) = \frac{\mu_0}{2\pi} I \ln\left(\frac{D}{e^{-1/4} r}\right)\ [Wb/m] \tag{4.10}$$

The inductance per phase for a transposed three-phase transmission line is

$$L_{phaseOHL} = \frac{\lambda_{int} + \lambda_{ext}}{I} = \frac{\mu_0}{2\pi} \ln\left(\frac{GMD}{GMR}\right)\ [H/m] \tag{4.11}$$

Where GMD (Geometric Mean Distance) substitute D for symmetrical arrangements. $GMD = D_{12} D_{23} D_{31}$. GMR (Geometric Mean Radius) is $GMR = e^{-1/4} r = 0.7788r$.

The total inductance for a cable is

$$L_{cable} = \frac{\mu_0}{2\pi}\left(\ln\left(\frac{2s_{cable}}{d}\right) + \frac{1}{4}\right) \tag{4.12}$$

Where the s_{cable} is the cube root of the spacing distance between the conductors in a 3-core cable. The conductor diameter is represented by d.

Capacitance emerge from the potential difference between two points. Figure 4.2 illustrates a conductor where r is the conductor radius and R is the the distance to ground. To determine the capacitance, the voltage needs to be evaluated.

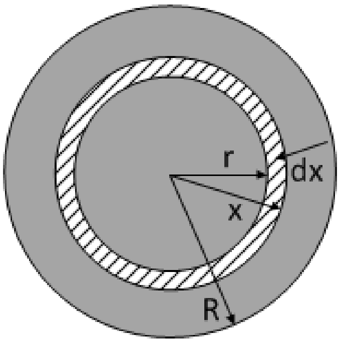


Figure 4.2: Geometry of a single core cable

The electric field flux density and electric field at a given point P outside the conductor is

$$\text{Density}_P = \frac{q}{A} = \frac{q}{2\pi x}\ [C] \tag{4.13}$$

Where q is the uniformly distributed charge on the surface of the conductor, A is the cross-section area of the conductor and x is the distance to the point P in meters. The electric field intensity E_P to a given point P is

$$E_P = \frac{\text{Density}_P}{\epsilon} = \frac{q}{2\pi\epsilon_0 x}\ [V/m] \tag{4.14}$$

Where $\epsilon = \epsilon_0 = 8{,}86 * 10^{-12}$ is the electric permittivity in vaccuum.

To calculate the voltage from the surface of a conductor, r , to ground, R, an integration of E_P is made. With this the capacitance can be calculated.

$$V = \int_r^R E_P\,\mathrm{d}x = \int_r^R \frac{q}{2\pi\epsilon x}\mathrm{d}x = \frac{q}{2\pi\epsilon}\ln\left(\frac{R}{r}\right)\ [V] \tag{4.15}$$

This gives an capacitance of

$$C = \frac{q}{V} = \frac{2\pi\epsilon}{\ln\left(\frac{R}{r}\right)}\ [F/m] \tag{4.16}$$

The distance from an OHL conductor with radius r to ground R is a lot higher than for a cable. The distance from conductor to ground is much smaller. This makes the capacitance higher for a cable according to (4.16).

The capacitance of a three core cable is not as easy to calculate analytically as for a single core. However, it is possible if the dielectric is uniform between the cores and the sheath. The capacitance is normally measured instead since the uniformity is not likely to be exact.

The sheath is usually grounded and the three conductors have nominal potential. This creates six capacitances within the cable. Three between sheath and conductors and three between the conductors, see Figure 4.3.

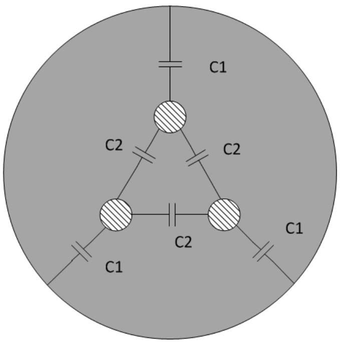


Figure 4.3: Capacitance of a three core cable

C_1 is the capacitance between sheath and conductor, C_2 is the capacitance between the conductors. Two measurements need to be done to find the two, see Figure 4.4. First, bundle the three conductors and measure between the bundle and sheath, this gives $C_x = 3C_1$. Second, ground any two conductors and measure between the sheath and the last conductor, this gives $C_y = 2C_2 + C_1$ [10].

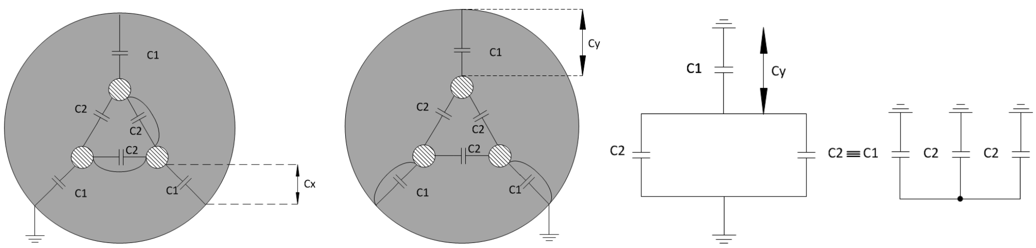


Figure 4.4: Measurements of three core cable

$$C_x = 3C_1 \tag{4.17}$$
$$C_y = 2C_2 + C_1 \tag{4.18}$$

This gives

$$C_1 = \frac{C_x}{3} \tag{4.19}$$
$$C_2 = \frac{1}{2}(C_y - C_1) \tag{4.20}$$
$$= \frac{1}{2}\left(C_y - \frac{C_x}{3}\right) \tag{4.21}$$

If measurements are not available the following formula based on empirical data gives an reasonable result for circular conductors [10].

$$C_0 = \frac{0.0299\epsilon_r}{\ln|1 + \frac{T+t}{d}\{3.84 - 1.70\frac{t}{T} + 0.52\frac{t^2}{T^2}\}|}$$

where ϵ_r = relative permittivity of the dielectric, d = conductor diameter, t = belt insulation thickness, T = conductor insulation thickness.

4.2 Shunt capacitance banks

To neutralize the inductive influence from OHLs, shunt capacitance banks (SCB) where installed. At power plants, it is standard to install SCBs to secure that asynchronous generators get the required amount of reactive power. SCBs are also used in substations to provide voltage support to the grid [9].

4.3 Zigzag transformer

A zigzag transformer has the function to create a neutral point. A three phase zigzag transformer is wounded as presented in Figure 4.5. Each winding of the transformer has the same amount of turns but the turns on each coil are turned in opposite direction. The first coil is connected to phases A, B, C. The second coil is connected together to create a neutral point. The first and second coil is connected A->B, B->C, C->A.

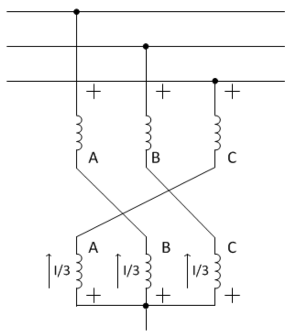


Figure 4.5: Three phase zigzag transformer

During normal operation the magnetic flux in the two coils cancel out each other. Low or a negligible current will flow in the neutral. During a SLG, the flux will no longer cancel out each other and a zero sequence current will flow from the fault through ground and in to the neutral point of the transformer [11].

Chapter 5

System Description and Modelling

The investigated system is located in Dalsland in Sweden. Total length of transmission lines in the system is approximately 44 km and has a nominal voltage of 11 kV. Most of the loads in the system are small summer houses with low consumption. The power is distributed both from the larger substation connecting the 140 to the 11 kV and through a small hydro power plant shown in Figure 5.1.

The substation has a number of incoming and outgoing lines. One of the outgoing lines feed the investigated line, it is a 11 kV line that ends 44 km north of the substation, see Figure 5.1.

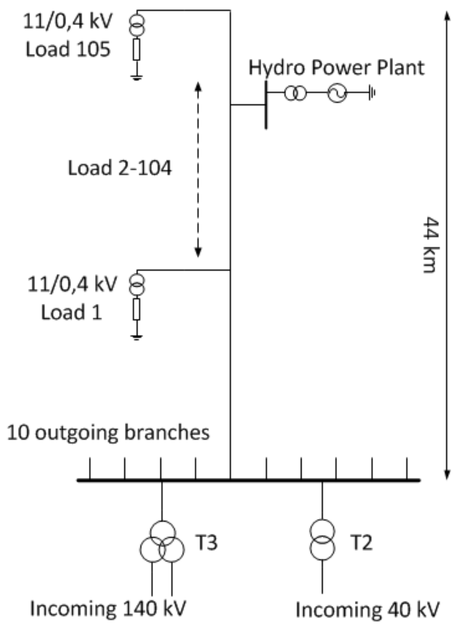


Figure 5.1: Circuit showing the investigated system

5.1 The substation

The substation feeding the system has ten outgoing 11 kV lines and two incoming lines, see Figure 5.2. L1 is the line that is subject to this project. Further, two shunt capacitance banks are installed, EK1 and EK2. They are used during heavy load time periods. EK1 is 3 MVAr and is often used during cold winters and other heavy load time intervals. EK2 is 2 MVar and is seldom used.

The system impedance at the substation is presented in Table 5.1 at 140 kV voltage level.

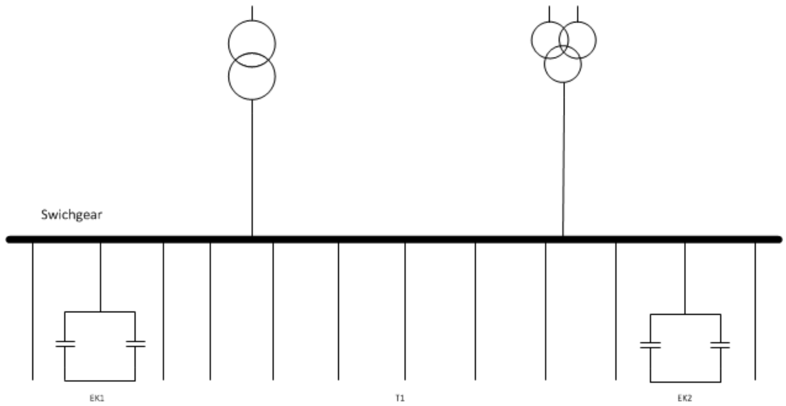


Figure 5.2: Simple circuit diagram of the Substation with outgoing lines and shunt capacitance banks

Table 5.1: System impedance for the substation at 140 kV voltage level.

System impedance data	
Resistance	3.06 Ω
Reactance	20.21 Ω
Impedance	20.45 Ω

The system is too large and too detailed to build and simulate in PSCAD for a master's thesis. Therefore, to be able to build a manageable model, it needs to be simplified. The simplified model is presented in Figure 5.3. The substation is represented using a voltage source and a two-winding transformer. The voltage source parameters are set to match the system impedance at the substation. Only two outgoing lines are simulated, line L1 and an adjacent line. All other connections in the substation are neglected since it is outside of the scope. When L1 is islanded, the contribution from the substation is insignificant.

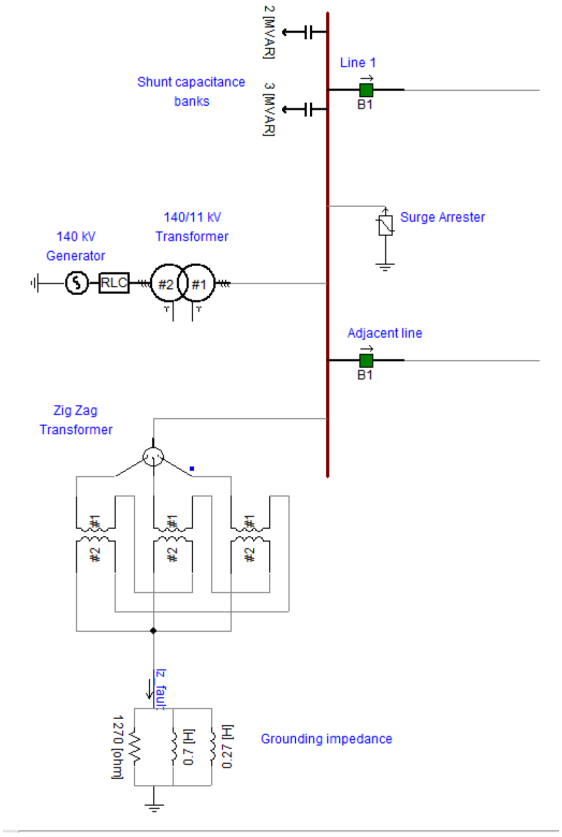


Figure 5.3: Model of the substation in PSCAD

5.2 Transformer and grid modelling

The power delivered to the system is supplied through two transformers at the substation. One of the transformers, T3, is a three winding transformer and the second, T2, is a two winding transformer. Transformer T2 is seldom used and has the function as backup transformer if T3 fails. The technical data for each transformer is presented in Table 5.2.

Table 5.2: Data for transformers at the substation

Transformer	T2	T3
Voltage [kV]	45±8x1,67%/11,5/0,42±5%	140±9x1,67%/46±2x2,5% /11,5±9x1,67%/0,42±5%
Windings	YNyn0+s	YNyn0yn0+syn0
Power [MVA]	16/16/0,1	40/40/20/0,1
P_k [kW]	80,3	138,4/71,4/70,1
u_k [%]	11,1	10,2/8,1/14,5
P_0 [kW]	9,2	24,7
i_0 [%]	0,124	0,14

The grid is represented by a 140kV AC voltage source and the transformer is represented by a 40 MVA 140/11kV two-winding transformer, see Figure 5.4. The AC voltage source PSCAD settings are presented in Table 5.3.

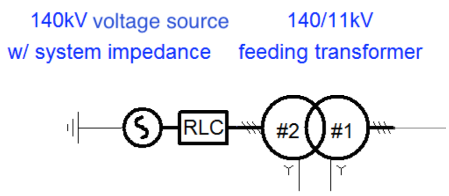


Figure 5.4: 140kV voltage source w/ system impedance and feeding 140/11kV transformer.

Table 5.3: Model specifications of the feeding generator at the substation

Feeding generator	
Type	R-L-C
Voltage (L-L,RMS)	140 kV
Voltage ramp up time	0.05 s
Frequency	50 Hz
Resistance, R	3,06 Ω
Inductance, L	63 mH
Capacitance, C	0 F

A zigzag transformer is installed on the secondary side of the transformer T3. A zigzag transformers function is to create a neutral point where zero sequence protection equipment is installed. The zigzag transformer built in PSCAD is presented in Figure 5.5.

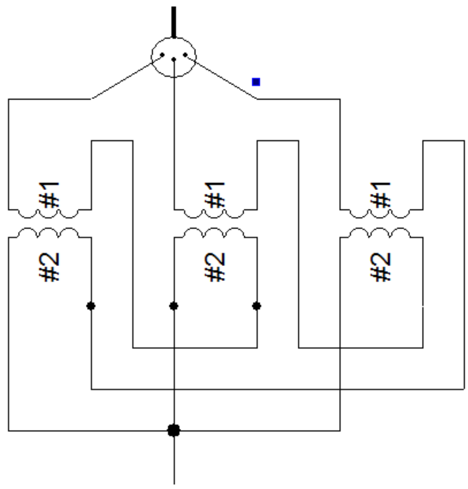


Figure 5.5: Zigzag transformer in PSCAD

The zero sequence impedance is built up by two inductive reactors and one resistance, all three are connected in parallel to ground. Data for components is presented in Table 5.4 [12].

Table 5.4: Data for zero sequence equipment at the substation.

Equipment	Range	Set value
Resistance	Fixed	1270 Ω
Permanent inductive reactor 1	Fixed	50 A
Adjustable inductive reactor 2	20-200 A	128 A

To implement the zero sequence equipment in PSCAD the equivalent inductances of the reactors are calculated using (5.1).

$$U = ZI \tag{5.1}$$

Where $U = 11kV$ is the L-L RMS system voltage, Z is the equivalent impedance and I is the rated current of the reactor. With (5.1) Z_{L1} and Z_{L2} are calculated.

$$Z_{L1} = \frac{U}{I_{L1}} = \frac{11kV}{50A} = 220\ \Omega \tag{5.2}$$

$$Z_{L2} = \frac{U}{I_{L2}} = \frac{11kV}{128A} = 85{,}94\Omega \tag{5.3}$$

Where I_{L1} and I_{L2} is the is the rated current of the reactors. Inserting (5.2) (5.2) in (5.4) will give the equivalent inductance.

$$L = \frac{Z}{j\omega} \tag{5.4}$$

Where $\omega = 2\pi f$, $f = 50Hz$ is the system frequency.

$$L_1 = \frac{Z_{L1}}{j\omega} = \frac{220}{2\pi 50} = 0{,}7H \tag{5.5}$$

$$L_2 = \frac{Z_{L2}}{j\omega} = \frac{85{,}94\Omega}{100\pi} = 0{,}27H \tag{5.6}$$

The resulting inductance together with the resistance is presented in a simple circuit diagram in Figure 5.6.

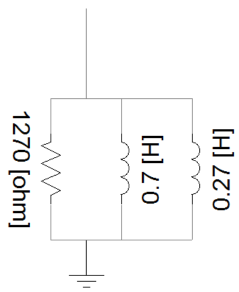


Figure 5.6: Equivalent circuit for the equipment at the substation

5.3 The hydro power plant

A small hydro power plant is connected to L1 and contributes to the power generation in the system. It has a 400 V, 400 kW asynchronous generator that is assumed to generate continuously. The AG has no control unit to balance the output. It is a constant torque on the shaft from the constant flow of water.

Two shunt capacitor banks of 60 kVAr each are connected to the generator to feed the generator with reactive power. Vattenfall has a policy that local generating units in a power system are not allowed to consume any reactive power from the grid.

The data for the hydro power plant is presented in Table 5.5.

Table 5.5: Technical data of the hydro power plant

	Hydro power plant	Transformer
Type	Asynchronous generator	ΔY
Voltage	0,4kV	10,5 $\pm 2x2.5\%/0.4kV$
Power	400kW	500kVA
Speed	615rpm	

The AG is represented by a induction machine in PSCAD, see Figure 5.7 It is set to start up at a continuous speed of 1.01 pu. This speed represent the continuous flow of the water through the station.

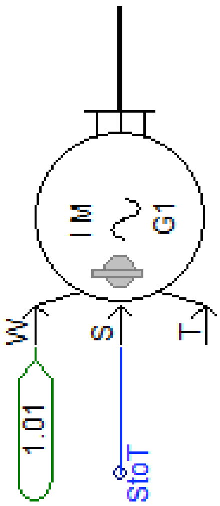


Figure 5.7: Generator setup for the hydro power plant

Where W, S, T is the three inputs on the machine. W is set-speed, T is set-torque and S selects speed or torque input.

5.4 Loads

The total amount of customers connected to the system are 105. They are fed through 31 11/0,4 kV transformers along L1. Every customers power consumption is known and to which transformer is connected to. The majority of the loads are summer houses with small consumptions (≈ 5 MWh/yr/house) [12]. A normal household in Sweden living in a house consume 25 MWh/yr and a normal household living in a apartment consume 12 MWh/yr [13].

Table 5.6: Customer consumption data to calculate average consumption per customer.

Customer consumption data	
Customers	105
Total consumtion	571886 kWh
Hours/year	8760 h

With this data the average yearly conumption in kW in the system is calculated with (5.7).

$$\text{Average yearly consumption} = \frac{571886}{8760} = 65 \text{ kW} \tag{5.7}$$

The loads characteristics are assumed be constant impedance loads in PSCAD, connected through a 11/0,4 kV, 100 KVA Δ/Y transformer to the system, see Figure 5.8. To have a less complicated simulation model the loads are assembled together into five loads, see Figure 5.9. The loads are marked with red circles. The location of the loads are based on geograpghical location.

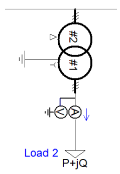


Figure 5.8: Model of a 11/0,4kV transformer and PQ-load.

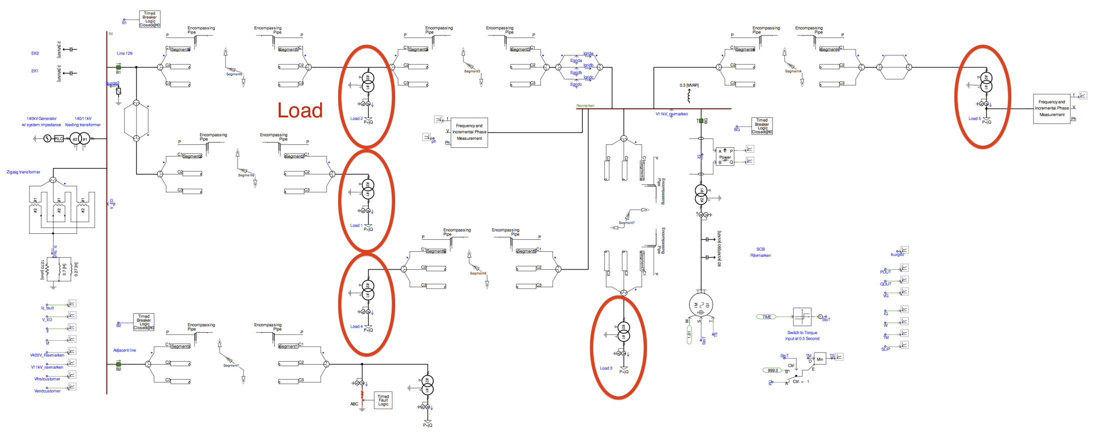


Figure 5.9: PSCAD model with the five loads marked with red circles.

Each loads power consumption is divided based on the amount of customers at a geographical location, see Table 5.7. A higher consumption means more customers at that location. One aspect in the system is that the load varies over the year. The loads are doubled or halved to demonstrade the variations in load in the simulation model.

Table 5.7: Load power consumption in the PSCAD model.

Load nr.	Average load [kW]	High load [kW]	Low load [kW]
1	10,1	20,2	5,05
2	26	52	13
3	6,2	12,4	3,1
4	7,3	14,6	3,65
5	15,4	30,8	7,7
Total	65	130	32,5

5.5 Cables

The system include nine different types of cables, each one with its own technical data. A total of 37 cable segments are installed throughout the system. The allocation of the segments and cable types are presented in Table 5.8. All cables are used at 11 kV. Cables with larger cross-section area are more common close to the substation where most of the power is distributed. As the loads becomes fewer along the line, the current in the cables gets lower. Therefore, as a result the cross-section area of the conductors decrease

[12].

Table 5.8: The nine different cable types used in the system and the length of it.

Cable	Total length in system [km]	Percentage of total length
AXAL-TT 240 [14]	8,6	19,7
AXAL-TT 50 [14]	6,7	15,3
AXAL-TT 150 [14]	5,7	13,0
AXAL-TT 95 [14]	5,5	12,5
AXLJ-RMF 25 [15]	8,2	18,7
AHXAMK-W [16]	1,9	4,5
AXCEL 95 [17]	2,3	5,3
AXCES 95 [18]	3,0	7,0
AXCEL 240 [17]	1,7	4,0
Total	43,7 km	100 %

The five most common cables are used in the PSCAD model. The cables, similar to the loads, are divided based on geographical location. Table 5.9 presents the cable type, length and capacitance in the simulation model.

Table 5.9: Caption

Name	Cable type	Length [km]	Capacitance [μF/km]	Capacitance [μF]
Segment 2	AXLJ RMF 25 [15]	8,4	0,19	1,60
Segment 3	AXAL-TT 150 [14]	7,5	0,33	2,48
Segment 4	AXAL-TT 50 [14]	4,6	0,22	1,01
Segment 5	AXAL-TT 240 [14]	17,1	0,40	6,84
Segment 6	AXAL-TT 50 [14]	4,6	0,22	1,01
Segment 7	AXLJ RMF 25 [15]	1,5	0,19	0,29
Total		43,7 km		13,23 μF

The cables total capacitance in the model is 13,23 μF. This gives a total reactance, X_c, of

$$X_c = \frac{1}{2\pi C} = \frac{1}{2\pi 50 * 13{,}23e-6} = 240{,}6\ \Omega \tag{5.8}$$

Where C is the total capacitance. With this the total reactive power from the cables, Q_c, becomes

$$Q_c = \frac{V_{RMS}^2}{X_c} = \frac{(11e3)^2}{240{,}6} = 0{,}503 \text{ MVAr} \tag{5.9}$$

Where V_{RMS} is the systems L-L RMS voltage. This shows an increase of 0,503 MVAr in reactive power from the cables.

5.6 Tripping times

All the outgoing lines from the substation are equipped with protection relays to prevent a potential fault at any line to propagate further into the rest of the system. The small hydro power plant is also equipped with a protection relay to disconnect the generator in the event of a fault. The time settings for the relays are presented in Table 5.10. The time settings are given by Vattenfall and are the settings from when a fault happened at an adjacent line [12].

Table 5.10: Time settings for protection relays when a fault occurs on an adjacent

Action	Time after fault [s]
Fault on adjacent line	0
Trip of adjacent line	0.7
Trip of Line 126	1.0
Trip of Hydro power station	1.3

Chapter 6

Simulation results and analysis

This chapter presents the simulated results from PSCAD. The focus of the result will be at the 0,4 kV side, since it is at this level the customers are connected. All plotted voltages are phase voltages.

An analysis of the simulated results is made to understand the impact and behaviour of power equipment and cables on the overvoltages. A comparison to OHL is also made to see the effect the transition have brought. Further, simulations are carried out on the fault that Vattenfall noticed, described in Section 1.1. Every simulation scenario is numbered with a case number in order to organise all simulations. Overvoltages are the main focus, but other possible effects are investigated including transients, unbalances, oscillations and fault locations.

A predefined amount of variations in the model are listed and changed. The variations being changed in the different cases are

- Higher/lower total load consumption
- Transformer saturation
- Shunt capacitance banks (connected/disconnected)
- Fault location - Fault on adjacent or investigated line

All cases are presented in Table 6.1. Every row is a new case and every column represents a change in the model. To get a good overview over the simulation scenario in an chronological order an illustrative timeline is created, see Figure 6.1.

Table 6.1: Simulated cases

Case	**Load [kW]**	**Transformer saturation**	**SCBs at Hydro Plant**	**EK1**	**EK2**	**Fault**
1	66	No	No	No	No	SLG Adjacent
2	66	No	Yes	No	No	SLG Adjacent
3	66	No	No	Yes	No	SLG Adjacent
4	66	No	Yes	Yes	No	SLG Adjacent
5	66	No	Yes	Yes	Yes	SLG Adjacent
6	66	No	No	No	No	SLG End of L1
7	66	No	Yes	No	No	SLG End of L1
8	66	No	No	Yes	No	SLG End of L1
9	66	No	Yes	Yes	No	SLG End of L1
10	66	No	Yes	Yes	Yes	SLG End of L1
11	66	Yes: 1,25	Yes	No	No	SLG End of L1
12	66	Yes: 1,25	Yes	Yes	No	SLG End of L1
13	66	Yes: 1,25	No	Yes	No	SLG End of L1
14	33	Yes: 1,25	No	Yes	No	SLG End of L1
15	33	Yes: 1,25	Yes	No	No	SLG End of L1
16	33	No	Yes	No	No	SLG End of L1
17	33	No	Yes	Yes	No	SLG End of L1
18	66	No	Yes	No	No	SLG End of L1
19	33	No	Yes	No	No	SLG End of L1
20	33	No	Yes	Yes	No	SLG Adjacent
21	33	No	Yes	No	No	SLG End of L1
22	66	No	Yes	No	No	L-L-L End of L1
23	66	No	Yes	Yes	No	L-L-L End of L1
24	66	No	Yes	Yes	No	L-L-L Adjacent
25	66	No	Yes	No	No	L-L-L Adjacent
26	66	No	No	No	No	L-L-L Adjacent

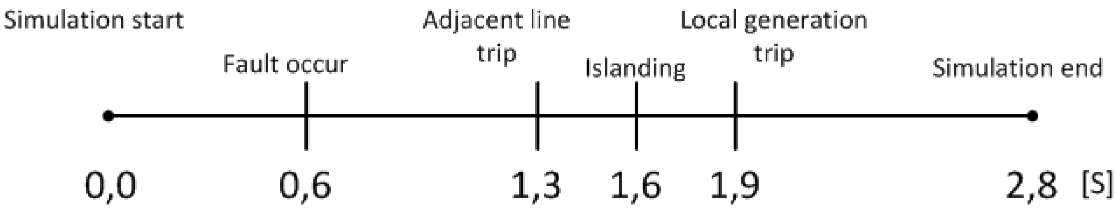
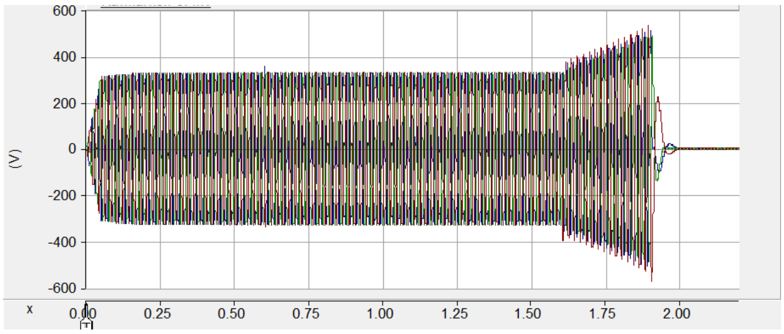


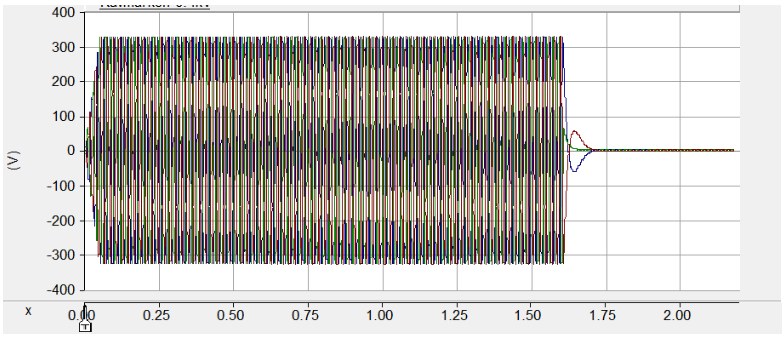
Figure 6.1: An example of the actions during simulations.

6.1 Influence of local generation

The hydro power plant is the only producing unit when L1 is islanded. A simulation is done to see the difference between when the power plant is connected to and when it is not during islanding, see Figure 6.2.



(a) Case 7 - Hydro power plant connected



(b) Case 29 - Hydro power plant disconnected.

Figure 6.2: Influence from the hydro power plant.

It is clear that the overvoltages are a result of the instability in the system and that the uncontrolled AG is a starting factor to the instabilities. After the system is islanded it has no support from the main grid and the voltage from the AG starts to increase.

It continuous to increase until it is disconnected. It consume reactive power from the SCBs and the cables as voltage support, see Figure 6.3. The electrical and mechanical torque are not in equilibrium as L1 is islanded. The first graph shows that the generator consumes (positive value) reactive power from the system to increase the voltage. It also produce active power (negative value).

As the water flowing through the station is continuous and delivers a constant mechanical torque, T_{mec} it is stable during islanding, see second graph. As shown in (6.1) T_{mec} is in relation to the electrical torque T_{el} and the acceleration $J\frac{d\omega}{dt}$. When the electrical torque drops, the AG accelerates to compensate for the drop in T_{el}.

$$T_{mec} = T_{el} + J\frac{d\omega}{dt} \tag{6.1}$$

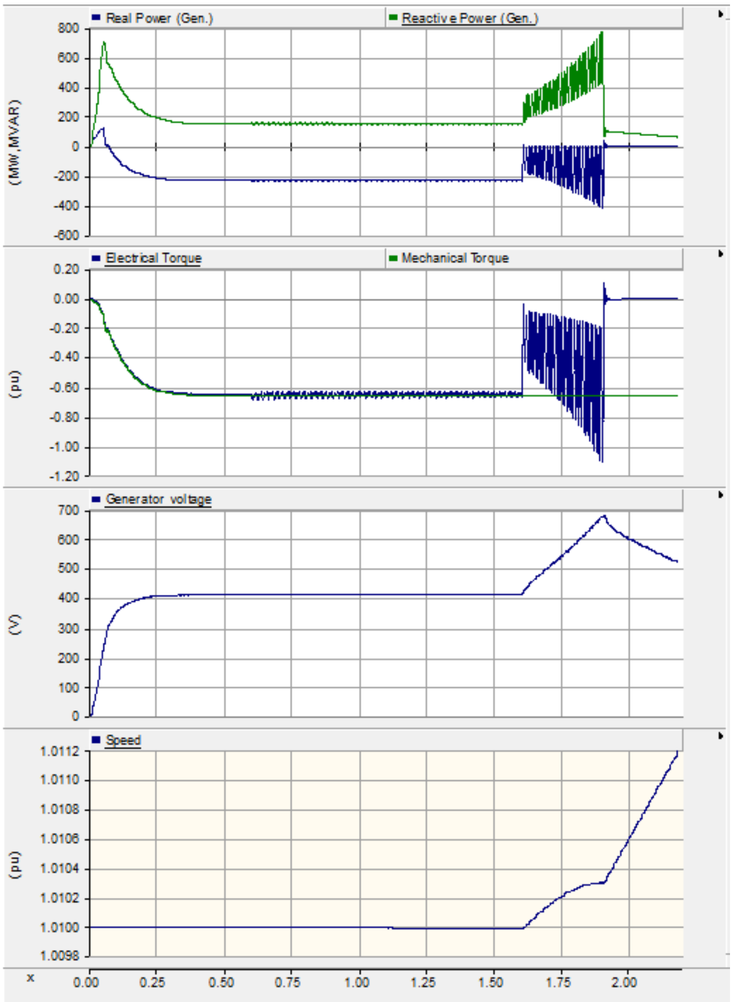


Figure 6.3: Case 7 - Generator measurements

The reactive power injection in the AG is shown in Figure 6.4. It is this injection of capacitor current that feed the generator and increases the voltage when it magnetize the generator.

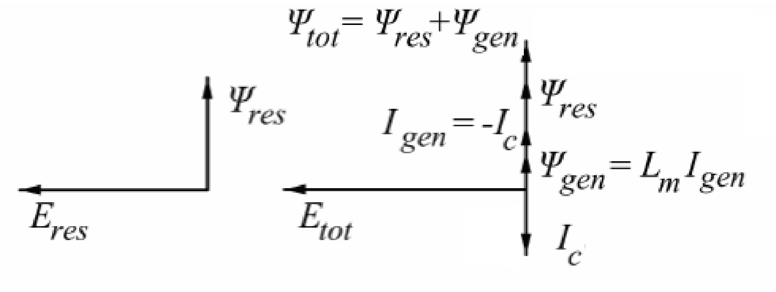


Figure 6.4: Phasor diagram showing the influence of capacitor current. Without to the left and added to the right [19].

I_c has the same size as the generated current I_{gen} with opposite sign. The generated flux Ψ_{gen} is increasing when the generated current is increasing. This result in a higher total flux Ψ_{tot} that magnetize the generator as is shown in Figure 6.5.

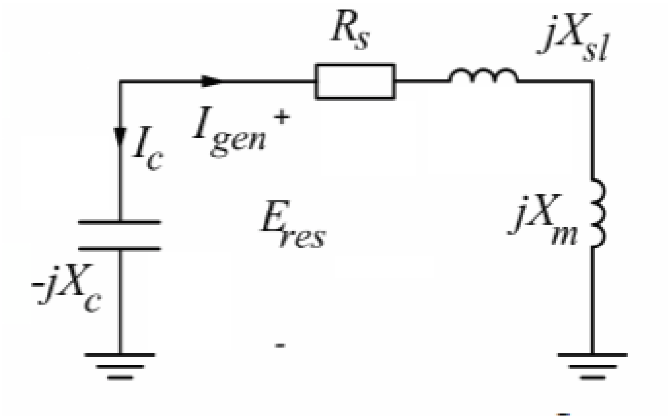


Figure 6.5: A single line diagram of the generator with shunt-capacitor [19].

6.2 Comparison OHL & Cables

A comparison is made to make it clear how much the capacitive power in cables contribute to the overvoltages. The OHLs conductor dimensions are matched to the most common cable in the system, AXAL-TT 240. The most accurate OHL dimensions extracted from a table over transmission line parameters has the name Hawk [20]. The extracted dimensions is presented in Table 6.2. Height from ground and distance between the lines are standard values for 11 kV OHLs and are shown in Figure 6.6.

Table 6.2: Dimensions of the OHLs

Code	Al Conductor $[mm^2]$	Strandings Al/Steel	DC Resistance $[m\Omega/km]$
Hawk	242	26/7	122,4

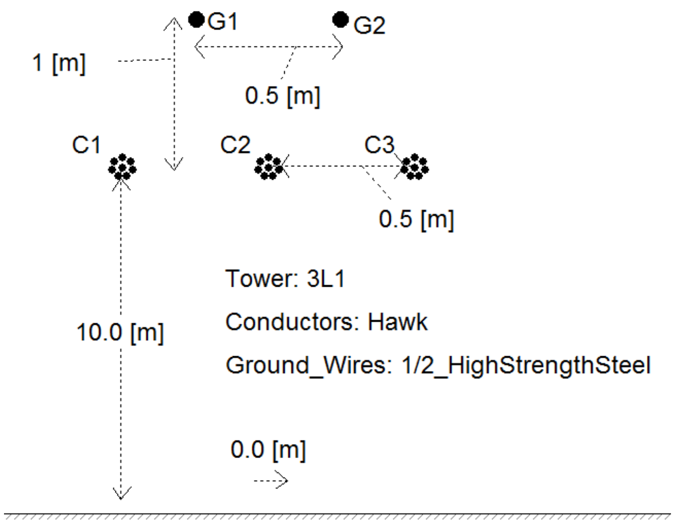
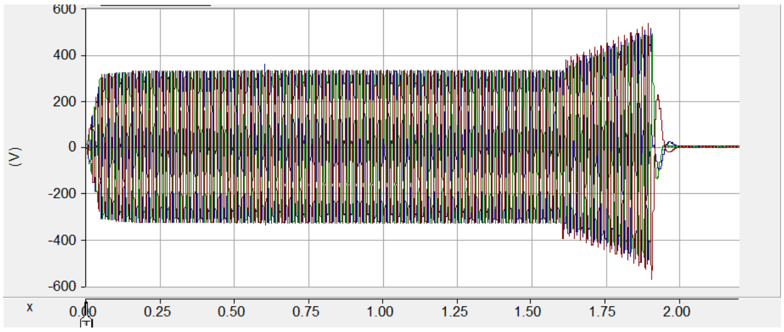
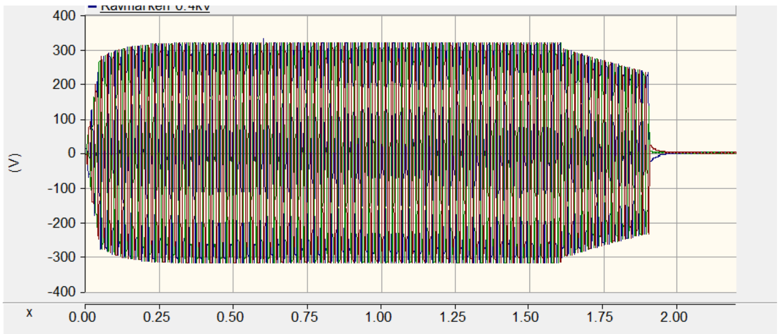


Figure 6.6: Geometry of OHL simulation cases

Worst case of overvoltages with average load (66 kW) and cables are shown in case 7. Comparing this with the same setup and OHLs (case 18) is presented in Figure 6.7. The highest measured overvoltage in case 7 is 531 V (375,5 V RMS) or 163% of nominal value. Case 18 has a highest voltage of 321,5 V (227,3V RMS) or 98,8% of nominal value.



(a) Case 7 - Cables



(b) Case 18 - OHLs

Figure 6.7: Comparison between cables and OHLs

The descending voltage in Figure 6.7(b) during islanding is due to a shortage of supporting reactive power. The graph show the lack of reactive power in the system and as a result the voltage decrease. There is not enough reactive power to support the voltage in the AG. Therefore, the consumed reactive power is zero, see Figure 6.8.

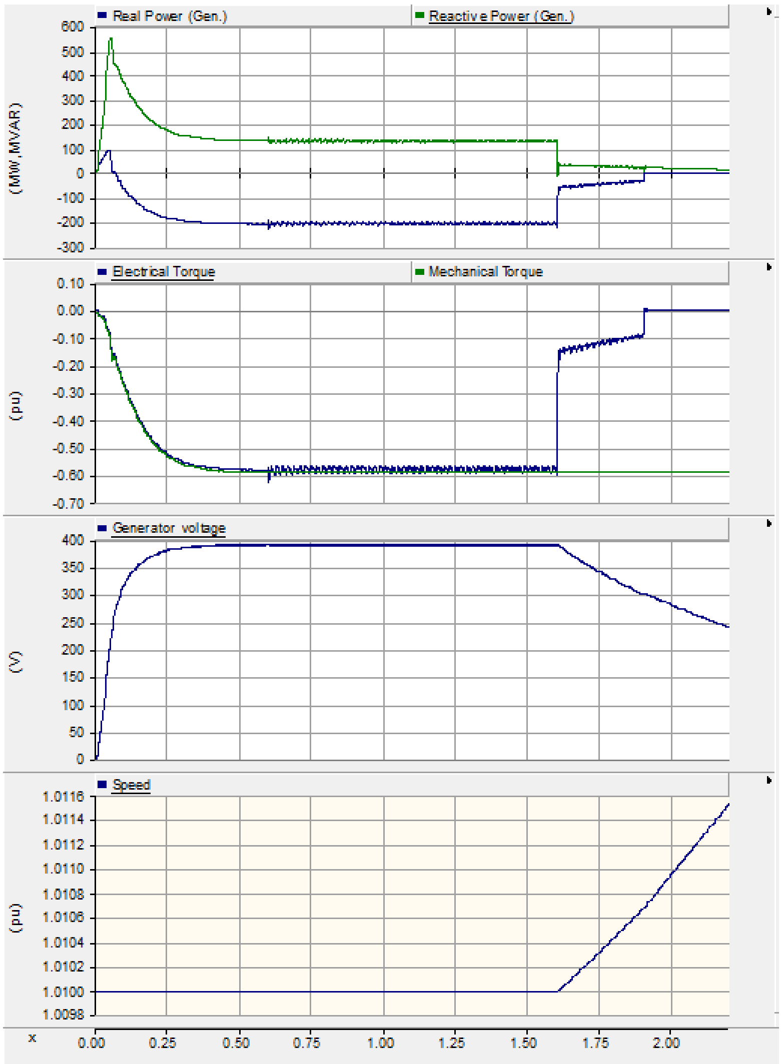
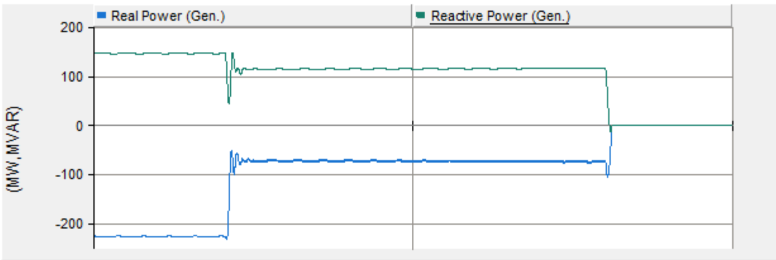


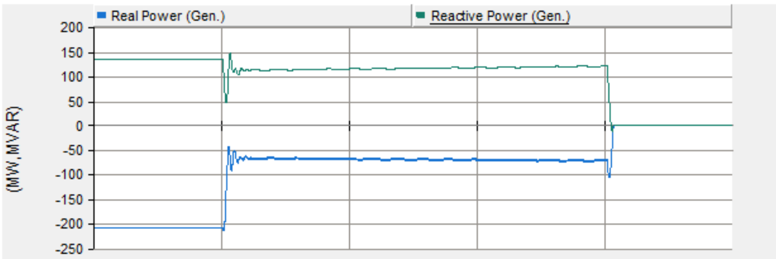
Figure 6.8: Case 18 - Generator measurements. The lack of reactive power makes the AG voltage to decrease.

As presented in Figure 6.8 and 6.3 the consumped reactive power of the AG either increase or decrease during islanding. With OHLs the reactive power decrease and with cables it increase. This implies that the capacitive power from the cables is the source of overvoltages.

Further investigations are made on the capacitance in the system. The capacitance from the cables are now represented by a delta connected capacitance at the AG. This further proves that it is due to an excessive amount of capacitive power in the system that result in overvoltages. Figure 6.9a represent case 1 with no SCBs connected and only cables present. Figure 6.9b represent case 1 with a SCB at the hydro power plant connected and only OHLs present. The SCB capacitance value is equal to the cables, as presented in Section 5.5. The reactive power consumption are the same in both cases.



(a) Case 1 - Active and reactive power at the AG with only cables in the system.



(b) Case 1 - Active and reactive power at the AG with only OHLs in the system and a 350 kVAr capacitor installed at hydro power plant.

Figure 6.9: The figure illustrates the consumption of reactive power at the AG in the hydro power plant. (a) illustrates a system all made of cables. (b) illustrates a system all made of OHLs and a capacitor installed.

6.3 Influence of shunt capacitance banks

The influence of SCBs on the overvoltages are simulated, especially the SCBs at hydro power plant since they are still connected during islanding. The influence of the SCBs at hydro power plant is presented in Table 6.3. A correlation to overvoltages is noticed when the SCBs at hydro power plant are connected. The only exception is when there is a fault on L1 and average load (Case 6). No SCBs are connected in case 6 and still overvoltages occur, see Figure 6.10. This demonstrates that the cables alone contributes with an excessive amount of reactive power.

During simulations with different SCBs connected or disconnected, overvoltages generally increased with a higher total capacitance in the system.

Table 6.3: All cases with overvoltages. A correlation between overvoltages and SCBs at hydro power plant are noticed.

Case	Total load [kW]	Saturated transformers	SCB Hydro Plant	SCB EK1	SCB EK2	Fault	Hydro Plant 0,4kV	Hydro Plant 0,4kV RMS	% of Nominel
16	33	No	Yes	No	No	SLG End of L1	621	439,1	190,9
21	33	No	Yes	No	No	SLG End of L1	621	439,11	190,9
7	66	No	Yes	No	No	SLG End of L1	531	375,5	163,2
17	33	No	Yes	Yes	No	SLG End of L1	507,5	358,9	156,0
15	33	Yes: 1,25	Yes	No	No	SLG End of L1	480,5	339,8	147,7
11	66	Yes: 1,25	Yes	No	No	SLG End of L1	463	327,4	142,3
10	66	No	Yes	Yes	Yes	SLG End of L1	456	322,4	140,2
20	33	No	Yes	Yes	No	SLG Adjacent	445	314,66	136,8
6	66	No	No	No	No	SLG End of L1	432	305,5	132,8
9	66	No	Yes	Yes	No	SLG End of L1	427	301,9	131,3
24	66	No	Yes	Yes	No	L-L-L Adjacent	420	296,98	129,12
31	66	No	Yes	No	No	No fault	412,8	291,89	126,91
25	66	No	Yes	No	No	L-L-L Adjacent	411	290,62	126,36
5	66	No	Yes	Yes	Yes	SLG Adjacent	392,5	277,5	120,7
4	66	No	Yes	Yes	No	SLG Adjacent	388	274,4	119,3
2	66	No	Yes	No	No	SLG Adjacent	380,6	269,1	117,0
12	66	Yes: 1,25	Yes	Yes	No	SLG End of L1	380,4	269,0	116,9

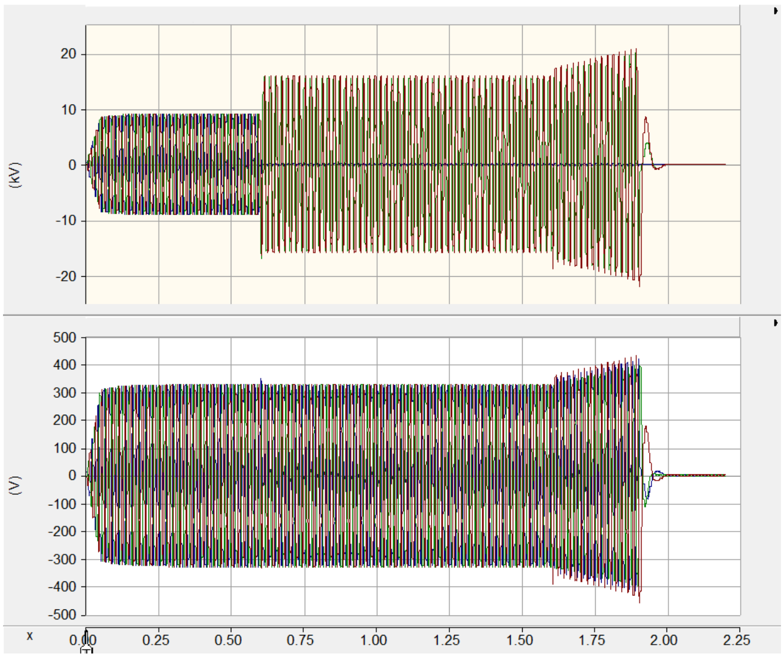


Figure 6.10: Case 6 - No SCBs connected. Even though no SCBs are installed overvoltages occur. The cables alone contribute with too much reactive power which result in overvoltages.

6.4 SLG fault on adjacent line

A SLG fault is introduced at the adjacent line and the load is average load, 65kW. Different quantities of SCBs are tested to see the effects on the overvoltages.

When the fault Vattenfall noticed occured EK1 and the SCBs at the hydro power plant are connected, see case 4. The resulting voltage is presented in Figure 6.11. The highest simulated voltage is 388 V (274 V RMS), or 119% of nominal value. Looking at Figure 6.11, a small voltage step is made at 0,6 s < t < 1,3 s from 334,3 V (236,4 V RMS) up to 345,9 V (244,6 V RMS). It is an increase of 3,5%. However, 244,6 V RMS is still within the approved limits. The voltage steps are present in a few of the simulated cases, and all are within the accepted limits.

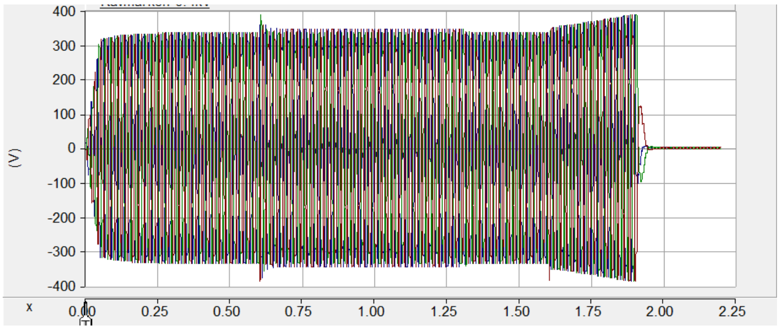


Figure 6.11: Case 4 - Voltage at 0,4 kV level. EK1 and the SCBs at the hydro power plant connected.

Another scenario is to connect SCB EK2 (case 5) this results in a slightly higher overall voltage, see Figure 6.12. The highest voltage noted here is 392,5 V (277,5 V RMS), or 120% of nominal value. This case is very unlikely to happen because EK2 is very seldom used as mentioned in Section 5.1.

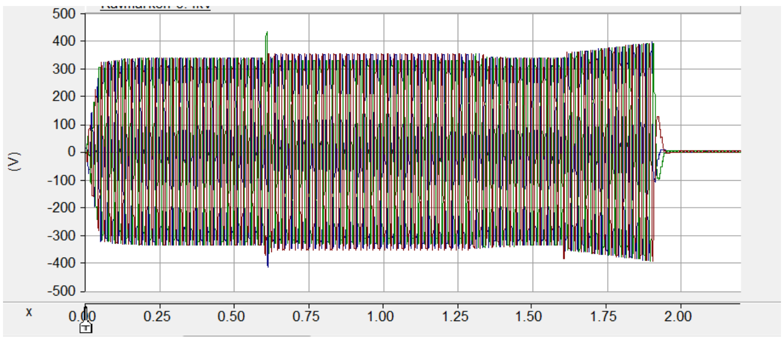
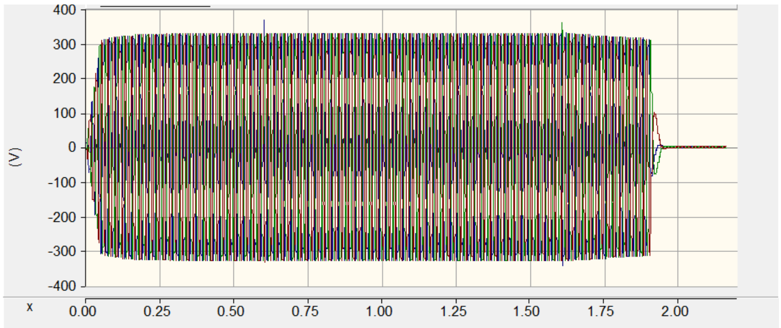


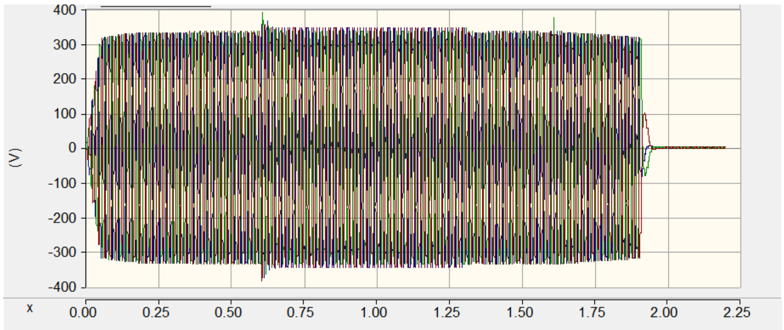
Figure 6.12: Case 5 - SCBs at the hydro power plant, EK1 and EK2 are connected.

The starting voltage for case 4 and 5, 333,5 V and 338 V are 102,6% and 104% of nominal value respectively. This shows in an increase of nominal voltage due to an abundance of reactive power in the system.

Not all cases result in overvoltages, case 1 and 3 stays within ±10%, see Figure 6.13. The difference between these cases and the ones described above is that the SCBs at the hydro power plant are disconnected. The measured values are 327,8 V (231,8 V RMS) or 100,8% of nominal value and 344,5 V (243,6 V RMS) or 105,9% of nominal value respectively for case 1 and 3.



(a) Case 1 - No SCBs



(b) Case 3 - SCB EK1 connected

Figure 6.13: Case 1 and 3 with no SCBs at the hydro power plant

6.5 SLG fault on L1

A SLG fault is in this case introduced at the end of L1. The simulations are done the same way as before.

The overall result from this setup is that the overvoltages increase in all cases. The highest overvoltage reached 531 V (375,5 V RMS) or 163% of nominal value in case 7, see Figure 6.14. This case only have the SCBs at the hydro power plant connected.

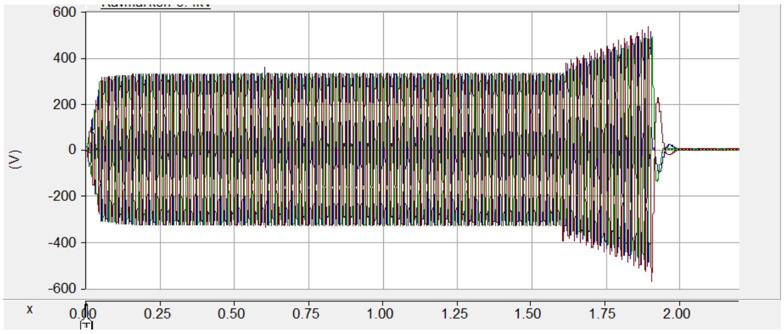


Figure 6.14: Case 7- SCB at the hydro power plant connected.

6.6 Three-phase fault

A three-phase fault is introduced at the end of L1. The three phase fault is a line-to-line-to-line, L-L-L, fault that for example can occur when a tree branch falls on all three phases.

With only the SCBs at the hydro power plant connected (case 22) resulted in no over-voltages. The result of the simulation is presented in Figure 6.15. When the fault occur all three phases goes down to a lower level and when L1 is islanded the system is short-circuited and the voltage level decrease to zero.

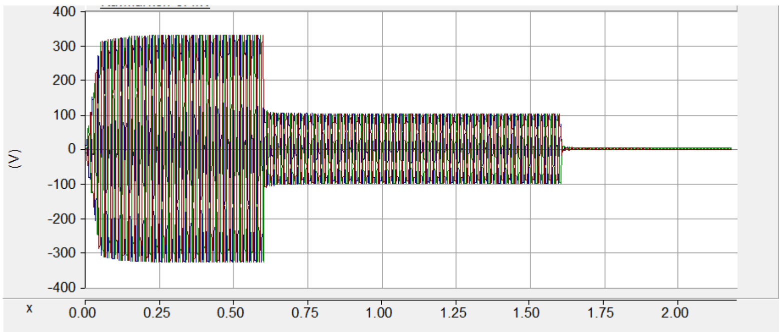


Figure 6.15: Case 22 - Only the SCBs at the hydro power plant are connected.

Connecting EK1 result in a similar voltage to case 22 above. The overall voltage level is a few numbers higher which is exprected due to the increase in reactive power support.

Further, a L-L-L fault is introduced on an adjacent line instead of L1 (case 25). The fault is disconnected together with the adjacent line at 1,3 s resulting in an increase of voltage, see Figure 6.16. When L1 is islanded the AG accelerate. The highest voltage level is 411 V (290,6 V RMS) or 126,4 % of nominal value .

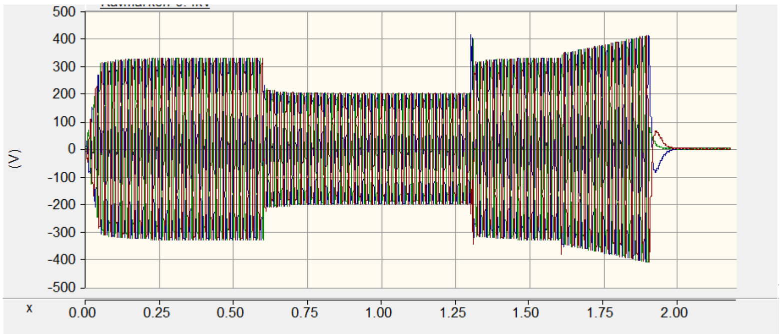


Figure 6.16: Case 25 - SCBs at the hydro power plant connected.

6.7 Load disconnection

This scenario investigating how the fault influence the overvoltage. It is proven that overvoltages occur during islanding because of a after fault. Now, no fault is present a spontaneous tripping is made. Tripping times are the same and only the SCBs at the hydro power plant are connected. The resulting voltage is presented in Figure 6.17.

The highest voltage is 412,8 V (291 V RMS) or 126,9 % of nominal value. This is 23 V higher compared to a SLG on adjacent line and 84 V lower compared to a SLG on L1. This shows that it is not because of a fault the overvoltages occur. It is enough to trip L1 in order to reach overvoltages. Although, islanding due to a fault gives a higher or a lower overvoltage depending on where the fault is.

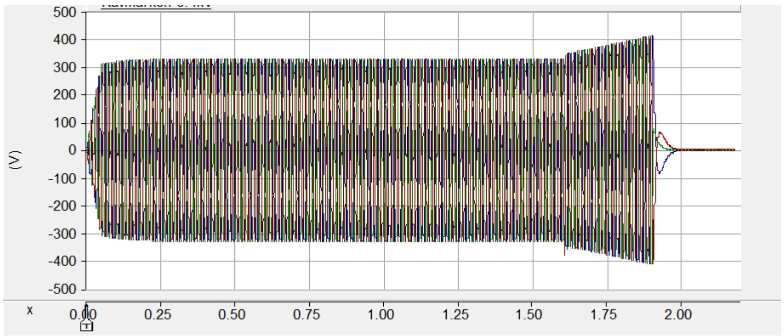


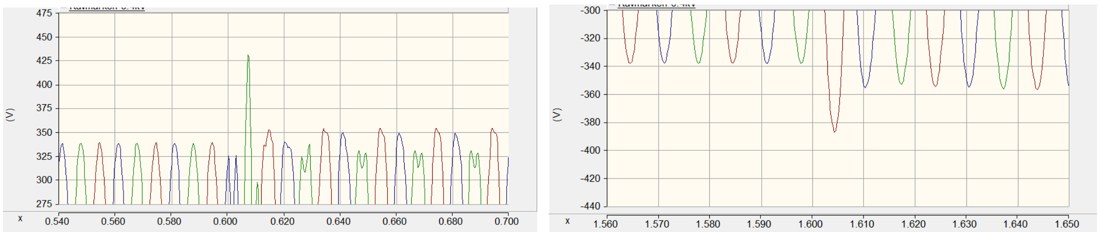
Figure 6.17: Case 31 - SCBs in at the hydro power plant connected with no fault present.

6.8 Transient overvoltages

Transients are present in the majority of the simulation cases, although the amplitude vary much. The transients occur at the same time during all of the simulations. A first transient is noticed at 0,6 s, when a fault occur. Second transient is at 1,6 s, when L1 is islanded. All transients occur during switching actions and are slow-front transients according to Section 2.4.

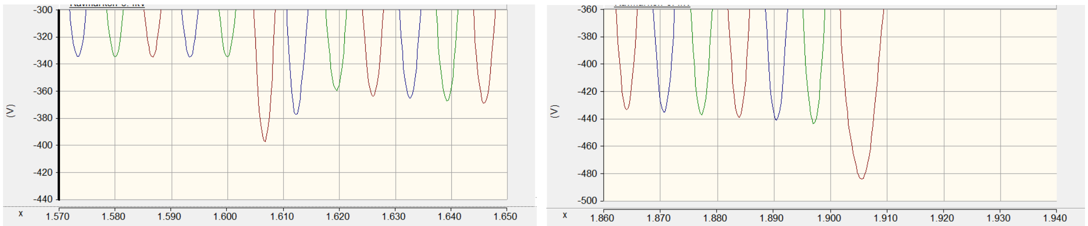
The worst transient occur in simulation case 5 and case 20, see Figure 6.18 and 6.19.

The amplitudes of the worst transients in case 5 and 20 are 431 V (Figure 6.18a) and 484,6 V (6.19a). This is 133% and 149% of nominal value.



(a) Positive transient **(b)** Negative transient

Figure 6.18: Case 5



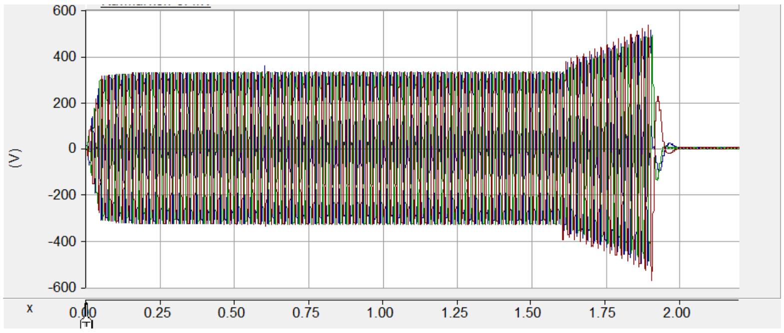
(a) Negative transient **(b)** Negative transient

Figure 6.19: Case 20

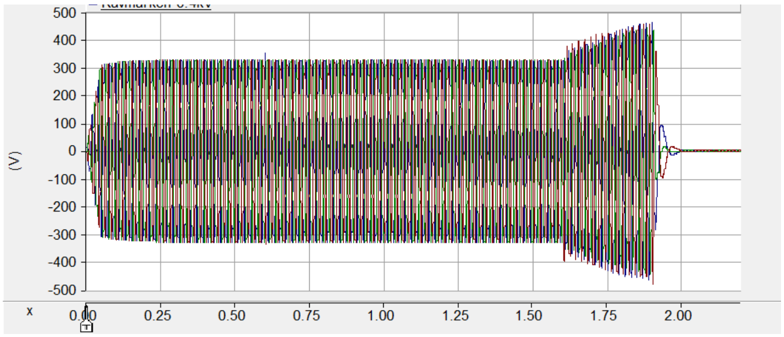
6.9 Saturated transformers

The 11/0,4 kV transformers along L1 is in an ideal case simulated with no saturation. In the following simulations the transformers has a knee voltage of 1,25 pu (the standard value in PSCAD). It results in an attenuating effect on the overvoltages. Comparing case 7 with case 11 shows an attenuating effect as L1 is islanded, see Figure 6.20.

The highest measured voltage in case 7 is 531 V (375,5 V RMS) or 163% of nominal value. The highest measured voltage in case 11 is 463 V (327,4 V RMS) or 142% of nominal value. The only difference between the cases are the knee voltage of 1,25 pu in the transformers in case 11.



(a) Case 7



(b) Case 11

Figure 6.20: Effect of saturated transformers in the model.

6.10 Table of results

In this section all the results from the simulations are presented, see Table 6.4.

Table 6.4: A summarizing table of the different simulation cases. The voltages are the highest measured voltage that is not a transient.

Case	Load [kW]	Saturated transformers	SCBs Hydro	SCB EK1	SCB EK2	Fault	Hydro 0,4kV RMS	% of Nominal	Transients	Oscillations	OHL/ Cable
1	66	No	No	No	No	SLG Adjacent	231.8	100.8	367.5	No	C
2	66	No	Yes	No	No	SLG Adjacent	269.1	117.0	354/-375	No	C
3	66	No	No	Yes	No	SLG Adjacent	243.6	105.9	389,8/372,6	Yes	C
4	66	No	Yes	Yes	No	SLG Adjacent	274.4	119.3	388/382	Yes	C
5	66	No	Yes	Yes	Yes	SLG Adjacent	277.5	120.7	431/387	Yes	C
6	66	No	No	No	No	SLG End of L1	305.5	132.8	350,5/390	No	C
7	66	No	Yes	No	No	SLG End of L1	375.5	163.2	355/396,4	No	C
8	66	No	No	Yes	No	SLG End of L1	246.8	107.3	-/369,4	Yes	C
9	66	No	Yes	Yes	No	SLG End of L1	301.9	131.3	-/392,5	Yes	C
10	66	No	Yes	Yes	Yes	SLG End of L1	322.4	140.2	-/-	Yes	C
11	66	Yes: 1,25	Yes	No	No	SLG End of L1	327.4	142.3	354,9/396	No	C
12	66	Yes: 1,25	Yes	Yes	No	SLG End of L1	269.0	116.9	-/373	Yes	C
13	66	Yes: 1,25	No	Yes	No	SLG End of L1	235.5	102.4	-/347,9	Yes	C
14	33	Yes: 1,25	No	Yes	No	SLG End of L1	251.3	109.3	-/414,3	Yes	C

Case	Load [kW]	Saturated transformers	SCBs Hydro	SCB EK1	SCB EK2	Fault	Hydro 0,4kV RMS	% of Nominal	Transients	Oscillations	OHL/ Cable
15	33	Yes: 1,25	Yes	No	No	SLG End of L1	339.8	147.7	360,2/-	No	C
16	33	No	Yes	No	No	SLG End of L1	439.1	190.9	360,3/-	No	C
17	33	No	Yes	Yes	No	SLG End of L1	358.9	156.0	-/602	Yes	C
18	66	No	Yes	No	No	SLG End of L1	227.33	98.8	-/-	No	O
19	33	No	Yes	No	No	SLG End of L1	228.18	99.2	334,2/-	No	O
20	33	No	Yes	Yes	No	SLG Adjacent	314.66	136.8	-/484,6	Yes	C
21	33	No	Yes	No	No	SLG End of L1	439.11	190.9	-/-	No	C
22	66	No	Yes	No	No	L-L-L End of L1	232.28	100.99	-/-	No	C
23	66	No	Yes	Yes	No	L-L-L End of L1	236.17	102.68	-/-	Yes	C
24	66	No	Yes	Yes	No	L-L-L Adjacent	296.98	129.12	516/-	Yes	C
25	66	No	Yes	No	No	L-L-L Adjacent	290.62	126.36	415/-	Yes	C
26	66	No	No	No	No	L-L-L Adjacent	237.59	103.30	440/-	No	C
28	66	No	Yes	Yes	No	L-L-L Adjacent	230.23	100,1	470/-	No	O
31	66	No	Yes	No	No	No Fault	291.89	126.91	-/378	No	C

6.11 Proposed actions

This section presents simulation results of proposed actions to remove the overvoltages.

6.11.1 Removal of SCBs

One action is to remove the SCBs. Since the reactive power is too high, this contributes in lowering it and decrease the overvoltages. The results in Table 6.5 represents four cases where the SCBs at the hydro power plant worsen the overvoltages.

Connecting only the SCBs at the hydro power plant (Case 2) results in an overvoltage of 269,1 V RMS or 117% of nominal value. Without any SCBs connected (case 1), the highest measured voltage during islanding is 231,8 V RMS or 100,8% of nominal value.

With only EK1 connected (case 3) results in an overvoltage of 243 V RMS or 105,9% of nominal. If EK1 and the SCBs at the hydro power plant are connected the voltage increase up to 274,4 V RMS or 119,3% of nominal value.

This clearly shows that the SCBs increase the overvoltages. A proposed action is to disconnect the SCBs at local generation in a system dominated by cables.

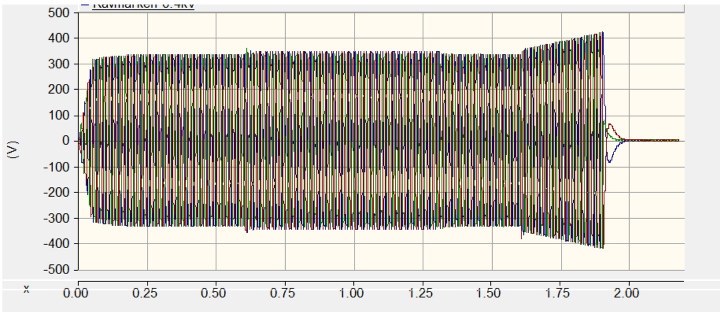
Table 6.5: Correlation between the SCBs at the hydro power plant and overvoltages are noticed.

Case	**Load [kW]**	**SCBs Hydro Plant**	**EK1**	**EK2**	**Fault**	**Hyrdo Plant nominal**
1	66	No	No	No	SLG Adjacent	100,8%
2	66	Yes	No	No	SLG Adjacent	117,0%
3	66	No	Yes	No	SLG Adjacent	105,9%
4	66	Yes	Yes	No	SLG Adjacent	119,3%

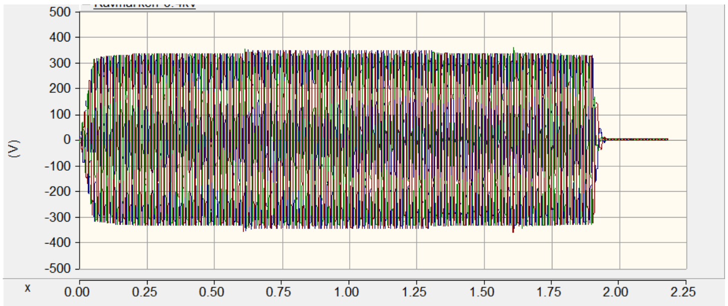
6.11.2 Install shunt reactor

Removing SCBs at local generation units are not enough in all distribution networks. It depends on the cables contribution in terms of reactive power. In the investigated system the removal of the SCBs at the hydro power plant is not enough, see Case 6 in Section 6.3. A proposed action is to install a shunt reactor to counteract the reactive power from the cables.

The suggestion is to install a reactor at the hydro power plant. The selection of location is based on where the source of overvoltages are. The size of the reactor is stepped up from zero until the overvoltages are within the limits. Simulations are made on Case 4 because this is the case with most reactive power installed. Figure 6.21 presents the influence of installing a shunt reactor. Break even is found with a shunt of 0,15 MVAr.



(a) 0,0MVAr



(b) 0,15MVAr

Figure 6.21: Case 4 - The effect on overvoltages when a shunt reactor is installed at the hydro power plant

6.11.3 Worst case scenario

Worst case of overvoltages occurred with Case 16, see Figure 6.22. This case has a low load (33 kW), SCBs at the hydro power plant connected and a fault on L1. Proposed actions are to disconnect the SCBs at the hydro power plant and install a shunt reactor of 0,15 MVAr. Simulations are done to investigate if this is enough to remove the overvoltages.

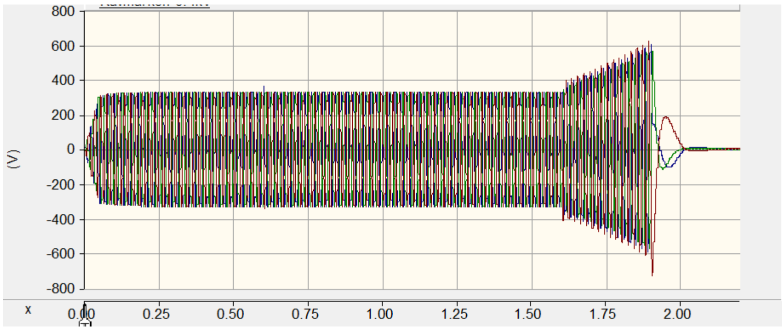


Figure 6.22: Case 16 - SCBs at the hydro power plant connected and SLG fault on L1.

Figure 6.23 presents the voltage when the SCBs at the hydro power plant are disconnected. By disconnecting the SCBs the highest voltage is reduced from 190,9 % of nominal value to 132,8 %.

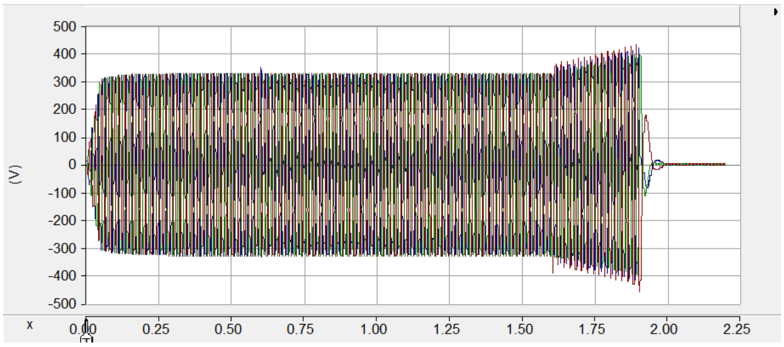


Figure 6.23: SCBs at the hydro power plant disconnected.

Figure 6.24 presents the voltage after installing a shunt reactor of 0,15 MVAr. The overvoltages are removed.

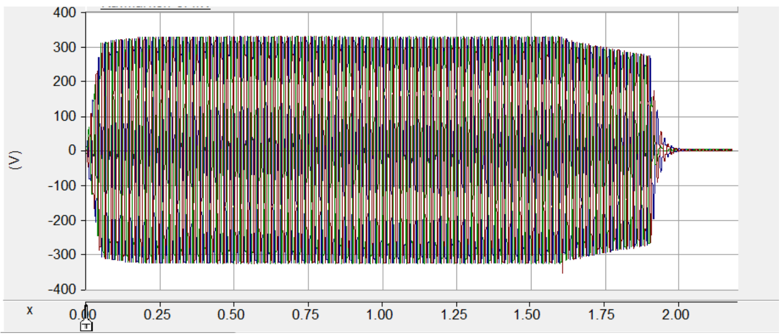


Figure 6.24: SCBs at the hydro power plant disconnected and a 0,15 MVAr shunt reactor installed instead.

Chapter 7

Conclusion

In this thesis it was investigated how a small distribution network with local generation behaves during islanding. A simulation model in PSCAD was build based on a real system in Dalsland. The focus of the study was to find overvoltages during islanding, and find one or more solutions to eliminate them. Simulations were executed on a number of scenarios with different network connections and fault locations.

The impact on the system from changing OHLs to cables, influence from SCBs and fault location are main case scenarios analysed. Overvoltages was present during a majority of the simulations. Worst case is when a SLG fault occur on L1 with a low load, cables and the SCBs at the hydro power plant connected (Case 16).

The results showed that it does not need to be a ground fault present in order to detect overvoltages. Simulations on islanding due to branch disconnection was made and showed similar result. This simulations showed an increased overvoltage compared to a SLG fault on an adjacent line and a lower voltage compared to a SLG fault on L1.

Due to that the overvoltages occured during the disconnection of the branch should henceforth be done with care. The disconnection together with the hydro power plant leads to overvoltages. Therefore the hydro power plant should always be disconnected before the branch is disconnected due to maintenance or testing.

The overvoltages propagate from the AG in the hydro power plant. As the branch is islanded the AG becomes unstable since the support from the main grid is disconnected. The output voltage from the AG is influenced strongly on the amount of reactive power fed to it. If the system is all made of OHL, it is inductive and consumes reactive power. Therefore the reactive power is taken from the AG and the voltage decrease. On the other hand, if the system is made of cables it generates reactive power. This will instead increases the output voltage.

In order to prevent the AG to increase in voltage, disconnection of local generation SCBs is proposed. Depending on the length of the cables and the reactive contribution from it, a shunt reactor needs to be installed for reactive power compensation. In the system investigated, a 0.15 MVAr shunt is proposed.

7.1 Future works

A deeper investigation on the AG needs to be performed to fully understand its behaviuour during islanding. It is possible to have the hydro power station as only producing source during islanding of L1. An investigation of AG control algorithms that may increase stability and reduce overvoltages can be done as well.

As mentioned in the scope, a simplification of the simulation model is made. In the future work a more detailed model should be made in order to increase the accuracy of the analysis.

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Appendix A

PSCAD overview

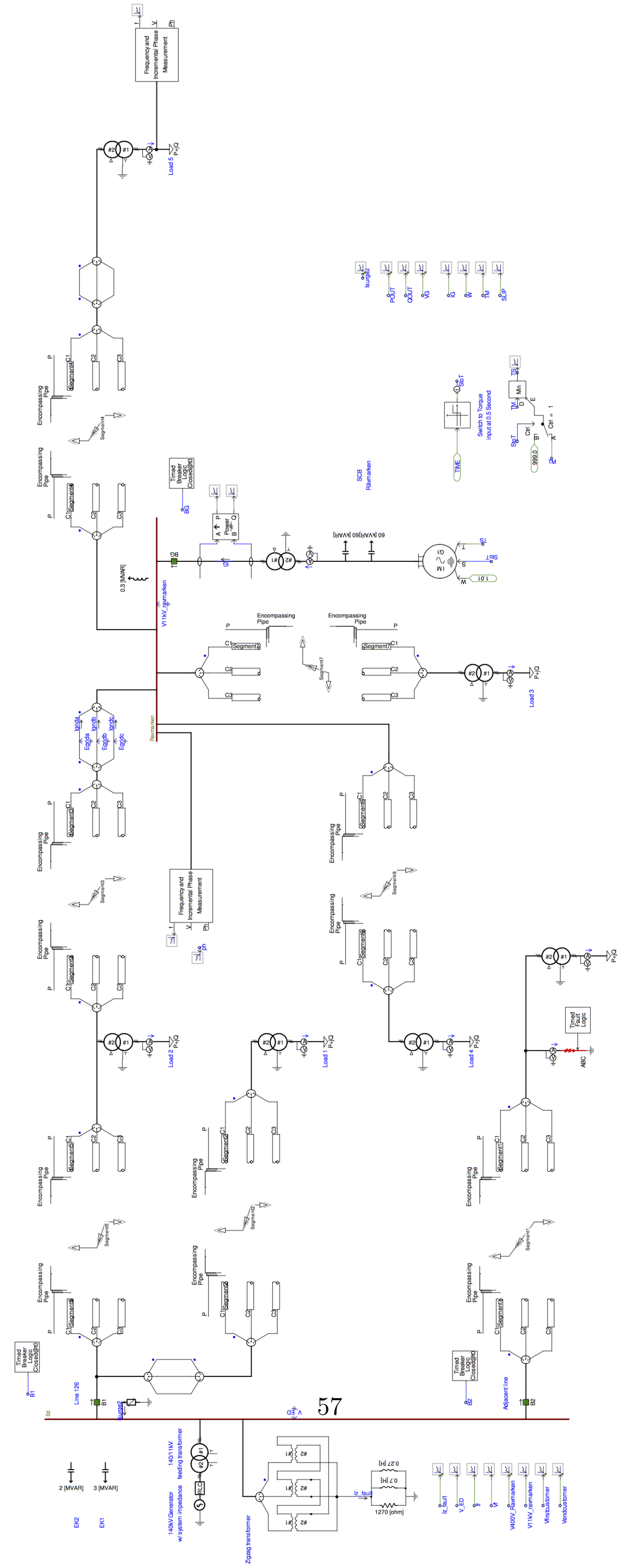

Figure A.1: PSCAD model over the system